United States
Environmental Protection
Agency

Air and Radiation
(6202J)

EPA 430-B-96-0004
September 1996

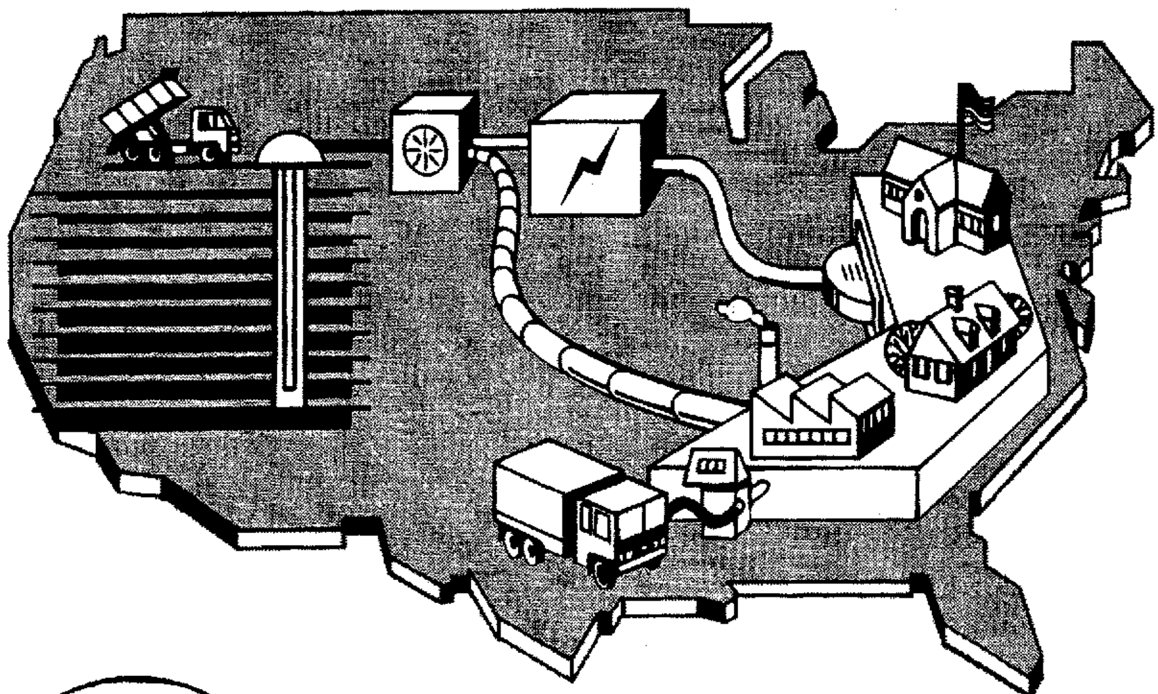
EPA

Turning a Liability into an Asset:

A Landfill Gas-to-Energy Project Development Handbook

Economic Analysis ◆ Financing

Contracting for Services



Choosing a Partner

LANDFILL METHANE
OUTREACH PROGRAM

Environmental Permitting ◆ Obtaining an Energy Sales Agreement

Internet Address (URL) • http://www.epa.gov

Recycled/Recyclable • Printed with Vegetable Oil Based Inks on Recycled Paper (20% Postconsumer)

Turning a Liability into an Asset:

A Landfill Gas-to-Energy Project Development Handbook

Landfill Methane Outreach Program

U.S. Environmental Protection Agency

September 1996

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF BOXES

ACKNOWLEDGEMENTS

This handbook was prepared with the assistance of numerous individuals. Staff at Boston Pacific provided technical expertise and provided the first draft of most of the document. Staff at ICF Incorporated compiled the chapters, reviewed and edited them, and produced the entire document.

PART I

PRELIMINARY ASSESSMENT OF PROJECT OPTIONS

The Project Development Process

Part I
Preliminary Assessment of
Project Options

Determining if a Project is Right for Your Landfill

Determining What Project Configuration is Right for Your Landfill

⇓

Part II
Detailed Assessment of
Project Economics

Evaluating Project Economics

Assessing Financing Options

Selecting a Project Development Partner

Winning/Negotiating an Energy Sales Contract

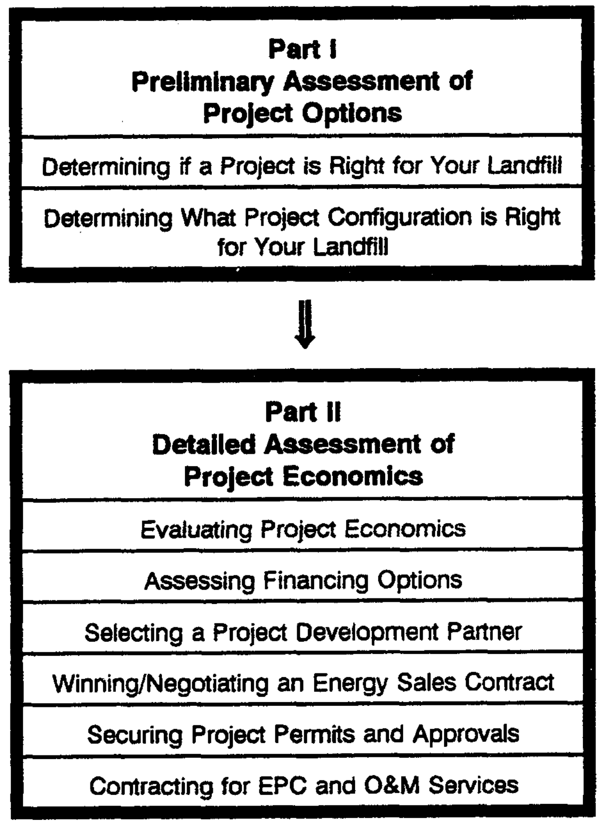
Securing Project Permits and Approvals

Contracting for EPC and O&M Services

1. INTRODUCTION

Each person in the United States generates about 4.5 pounds of solid waste per day — almost one ton per year. Most of this waste is deposited in municipal solid waste landfills. As this landfilled waste decomposes (a process that may take 30 years or more), it produces landfill gas. Landfill gas contributes to the formation of smog and poses an explosion hazard if uncontrolled. Furthermore, because landfill gas is about 50 percent methane, it is both a potent greenhouse gas and a valuable source of energy.

The Project Development Process



Substantial opportunities exist across the country to harness this energy resource and turn what would otherwise be a liability into an asset. The purpose of this handbook is to help landfill owners, operators, and others considering landfill gas projects determine whether landfill gas energy recovery is likely to succeed at a particular landfill, and to clarify the steps involved in developing a successful project.

The handbook is organized according to the process of landfill gas project development, as the flowchart on this page illustrates. It contains two major sections: **Part I — Preliminary Assessment of Project Options** provides the landfill owner/operator with basic screening criteria to assess the viability of a landfill energy recovery project and make a preliminary economic comparison of the primary energy recovery options; and **Part II — Detailed Assessment of Project Options** outlines and discusses the major steps involved in development of a landfill gas energy recovery project, from estimating expenses and revenues to constructing and operating the project. The flowchart on this page can be found at the front of each chapter, with the current section and chapter highlighted. Additional information is contained in Appendices A through J of the handbook.

1.1 THE BENEFITS OF LANDFILL GAS ENERGY RECOVERY

Landfill gas energy recovery offers significant environmental, economic, and energy benefits. These benefits are enjoyed by many, including the landfill owner/operator, the project developer, the energy product purchaser and consumer, and the community living near the landfill.

1.1.1 Environmental Benefits

Landfill gas contains volatile organic compounds, which are major contributors to ground-level ozone and which include air toxics. When little is done to control them, these pollutants are continuously released to the atmosphere as waste decomposes. When landfill gas is collected and burned in an energy recovery system, these harmful pollutants are destroyed.

Regulations already require many landfills to collect their landfill gas emissions, and new federal air regulations will soon require additional control. Once the gas is collected, landfill owner/operators have two choices: (1) flare the gas; or (2) produce energy for sale or on-site use. Both options address local air quality and safety concerns, but only energy recovery capitalizes on the energy value of landfill gas, while displacing the use of fossil fuels. Offsetting coal and oil use further reduces emissions of a number of pollutants, including sulfur dioxide, a major contributor to acid rain, as well as the production of ash and scrubber sludge from utilities. Furthermore, landfill gas collection systems operated for energy recovery are often more carefully managed than those designed to flare the gas. This means that more of the gas generated in the landfill may be collected and combusted, with fewer emissions to the atmosphere.

Landfill gas energy recovery also has the potential to significantly reduce the risk of global climate change. Landfill gas is the single largest source of anthropogenic methane emissions in the United States, contributing almost 40 percent of these emissions each year. Reducing methane emissions is critical in the fight against global climate change because each ton of methane emitted into the atmosphere has as much global warming impact as 21 tons of carbon dioxide over a 100 year time period. In addition, methane cycles through the atmosphere about 20 times more quickly than carbon dioxide, which means that stopping methane emissions today can make quick progress toward slowing global climate change.

1.1.2 Economic Benefits

New federal regulations, promulgated in March 1996, require several hundred landfills across the country to collect and combust their landfill gas emissions. Once installation and operation of a collection system is a required cost of doing business, incurring the extra cost of installing an energy recovery system becomes a more attractive investment. Sale or use of landfill gas will often lower the overall cost of compliance and, when site-specific conditions are favorable, the landfill may realize a profit.

More widespread use of landfill gas as an energy resource will also create jobs related to the design, operation, and manufacture of energy recovery systems and lead to advancements in U.S. environmental technology. Local communities will also benefit, in terms of both jobs and revenues, through the development of local energy resources at area landfills.

1.1.3 Energy Benefits

Landfill gas is a local, renewable energy resource. Because landfill gas is generated continuously, it provides a reliable fuel for a range of energy applications, including power generation and direct use. Electric utilities that participate in landfill gas-to-energy projects can benefit by enhancing customer relations, broadening their resource base, and gaining valuable experience in renewable energy development. Landfill gas power projects provide important demand side management benefits, as transmission losses from the point of generation to the point of consumption are negligible. The National Association of Regulatory Utility Commissioners recognized the value of landfill gas as an energy resource when it adopted a resolution in March 1994, "urging regulators to focus their regulatory attention on the landfill gas resources in their States to determine the role that energy from landfill gas can play as an energy resource for utilities and their customers." Industrial facilities, universities, hospitals, and other energy users can benefit by tapping into landfill gas, a low-cost, local fuel source.

1.2 THE EPA LANDFILL METHANE OUTREACH PROGRAM

The EPA Landfill Methane Outreach Program encourages landfill owner/operators to develop landfill gas energy recovery projects wherever it makes economic sense to do so. EPA estimates that over 700 landfills across the United States could install economically viable landfill gas energy recovery systems, yet only about 140 energy recovery facilities are in place. Through the Outreach Program, EPA is working with municipal solid waste landfill owners and operators, states, utilities, industry and other federal agencies to lower the barriers to economic landfill gas energy recovery.

This handbook is one component of the Landfill Methane Outreach strategy for overcoming information barriers to development of energy recovery projects. By providing information that can be used to assess project feasibility and outlining the project development process to landfill owner/operators and others considering energy recovery projects, this handbook can help spur development of successful projects. For more information on the Outreach Program, contact EPA's Hotline at 1-888-STAR-YES.

1.3 HOW TO USE THIS HANDBOOK

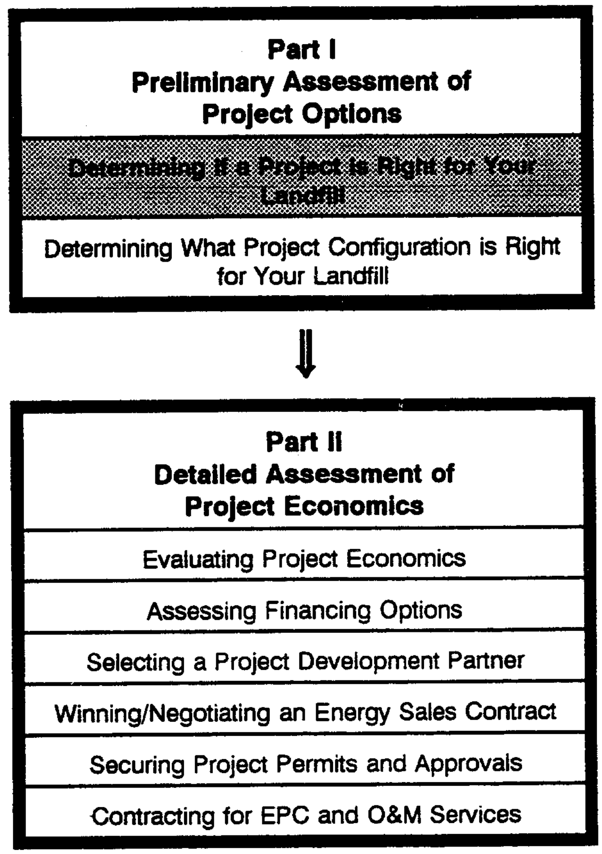
If you are a landfill owner/operator — or anyone considering a landfill gas-to-energy project — you can use this handbook to conduct a preliminary assessment of the potential for your landfill to support an energy recovery project. First, review Section 2.1 with the parameters of your landfill in mind. If your landfill meets the basic screening criteria (or has site-specific factors that make it a good candidate for energy recovery), use the information provided in Section 2.2 to develop a rough estimate of available landfill gas. Next, examine the economic comparison in Chapter 3, referring to the landfill gas estimate closest to that for your landfill, and determine which energy recovery option may be most cost-effective. Finally, carefully review Part II of the handbook (Chapters 4 to 10) to gain an understanding of the steps involved in developing an energy recovery project at your landfill. You may want to consult some of the references listed in Appendix H for more detailed information on the gas being generated at your landfill and the collection and energy recovery system you are considering.

This handbook is not meant to be an exhaustive guide to the landfill gas development process, nor is it a technical guide to project design. Once you have decided to pursue a gas-to-energy project, you may want to consult experts with experience in project development as well as technical resources regarding construction, equipment, operation, and other aspects of project design. The Landfill Methane Outreach Program can provide you with a list of landfill gas-to-energy project developers, engineers, equipment manufacturers, financiers, and end-users, and Appendix G contains a listing of organizations that can refer you to additional experts in project design, development, and operation.

2. DETERMINING IF A PROJECT IS RIGHT FOR YOUR LANDFILL

The preliminary assessment of project options includes two major phases. First, the landfill owner/operator must determine whether a project is likely to succeed at his or her landfill. If the landfill meets the criteria for a conventional energy recovery project — or has other characteristics that make it a good energy recovery candidate — the owner/operator next determines what project configuration would be most cost-effective. This chapter describes the steps involved in the first of these phases.

The Project Development Process



Determining if an energy recovery project may be right for a particular landfill is the first phase involved in assessing project options, as shown in the flowchart on this page. This phase involves two steps:

(1) application of basic screening criteria to determine if the landfill has the characteristics that apply generally to successful landfill gas energy recovery projects; and

(2) estimation of the quantity of landfill gas that can be collected, as gas quantity is a critical factor in determining whether landfill gas energy recovery is a viable option.

The approximately 140 landfill gas energy recovery projects operating in the United States exhibit a wide range of landfill characteristics and gas flows, illustrating that many different types of landfills can support successful projects. Nevertheless, there are a few basic criteria that can be used for site screening to determine whether a project is *likely* to succeed at a particular landfill. For example, a large landfill that is still receiving waste will, in general, be an attractive candidate for landfill energy recovery. These and other criteria, and how to apply them, are discussed in Section 2.1.

For landfills that appear to be candidates for energy recovery, estimating landfill gas flows is essential. The amount of gas that can be collected is dependent upon a number of factors, including, among others, the amount of waste in place, the depth of the landfill, the age and status of the landfill, and the amount of rainfall the landfill receives. There are several ways to estimate landfill gas quantity, ranging from "back of the envelope" calculations to sophisticated computer modeling. Not surprisingly, both the degree of certainty that collected gas quantity will match the estimate and the cost of developing the estimate increase along this spectrum. Section 2.2 describes some of the various methods available to estimate the gas generation and collection rate.

If the landfill under consideration for energy recovery already has a gas collection system that is likely to be representative of the area from which gas will be drawn (i.e., not just perimeter wells), the task of estimating gas quantity is essentially complete. The quantity of gas collected with the current system can be used to estimate the amount of gas available for energy recovery.

2.1 STEP 1: BASIC SCREENING FOR PROJECT POTENTIAL

The purpose of basic screening is to quickly identify landfills that are good candidates for energy recovery. The questions in Box 2.1 can help guide a landfill owner/operator through the process of evaluating screening criteria, which are identified below. It is likely that the best candidates for energy recovery will have the following characteristics:

- At least one million tons of waste in place;
- Still receiving waste, or closed for not more than a few years; and
- Landfill depth of 40 feet or more.

Landfills that meet these criteria are likely to generate enough landfill gas to support a gas-to-energy project. An industry rule of thumb places the "economically viable" gas generation rate at one million cubic feet per day (1 mmcf/day). However, this figure, like the screening criteria, should be considered only as a guideline — in fact, many landfills that do not meet all of the criteria could support successful energy recovery projects because of important site-specific characteristics. For example, energy recovery projects are currently underway at landfills with as little as 50,000 tons of waste in place, gas flows of 20,000 cf/day and depths of just 10 feet. In addition, about forty percent of existing and planned projects are sited at closed landfills, with about half of these closed during the 1980s [Berenyi and Gould, 1994].

Landfills that already collect their landfill gas, or that will be required to collect the gas, may be attractive candidates for energy recovery, especially if they meet most or all of the other criteria. Once installation and operation of a collection system is a required cost of doing business, the extra cost of energy recovery becomes a more attractive investment. In this situation, energy recovery may be the most cost-effective compliance strategy, even if it does not provide a net profit.

Some additional characteristics may also be indicative of energy recovery potential. These include:

- Climate: Moisture is an important medium for the bacteria that break down the waste. In areas with very low rainfall (i.e., less than 25 inches per year), yearly generation of landfill gas is likely to be relatively low. Therefore, less gas may be available for energy recovery each year at arid landfills (although gas production may continue for a longer period of time than in a wetter environment).

- Waste Type: Methane is generated when organic waste, such as paper and food scraps, decomposes. Therefore, landfills (or cells within landfills) that contain

Box 2-1 Is a Project Right for Your Landfill?

A. Is your landfill a municipal solid waste landfill?

If not, you may encounter some additional issues in project development due to the presence of hazardous or non-organic waste in the landfill. Stop and consult an energy recovery expert.

B. Add your score for the next 3 questions:

1. How much waste is in your landfill? **Score**

Tons	Score
≥ 3 million	40
1-3 million	30
0.75-1 million	20
< 0.75 million	10

______

2. Is your fill area at least 40 feet deep?
   Yes = 5
   No = 0

   \+ ______

3. Is your landfill currently open? If yes, answer 3(a). If no, answer 3(b).

   (a) How much waste will be received in the next 10 years? For each 500,000 ton, score 5 points. + ______

   (b) If closed < 1 year, enter 0. If closed ≥ 1 year, multiply each year since closure by 5, and subtract that amount from the total. - ______

Total your answers to questions 1-3: = ______

C. If your score is:

≥ 30: Your landfill is a good candidate for energy recovery (go to section D).

20-30: Your landfill may be a good candidate for energy recovery, particularly if a factory or other energy user with constant fuel demand is located within a few miles of the landfill (go to Section D).

< 20: Your landfill may not be a good candidate for conventional energy recovery options. However, you may want to consider on-site or alternative uses for the landfill gas.

D. If your landfill is a good candidate, answer the following questions:

1. Are you now collecting gas at your landfill (other than from perimeter wells), or do you plan to do so soon for regulatory or other reasons? If yes, your landfill may be an excellent candidate for energy recovery.

2. (a) Is annual rainfall less than or equal to 25 inches per year?
   (b) Is construction and demolition waste mixed into the municipal waste or is it a large portion of total waste?

If yes to questions D.2(a) or D.2(b), your annual landfill gas production may be lower than otherwise expected. Your landfill may still be a strong candidate, but you may want to lower your estimated gas volumes slightly during project design and evaluation.

large proportions of synthetic or slowly-decomposing organic waste, such as plastic and construction/demolition waste, may be less attractive candidates for energy recovery.

- <u>Nearby Energy Use</u>: A smaller landfill may still be a good candidate for energy recovery if there is a use for the gas at or near the landfill. Such landfills should not be discounted without exploration of direct gas use options.

2.2 STEP 2: ESTIMATING GAS QUANTITY

Once the landfill owner/operator has determined that energy recovery may be attractive, the next step is to estimate landfill gas flow. Information from this step is of critical importance in determining the technical specifications of the project and in assessing its economic feasibility. There are a variety of methods, ranging from very basic desktop estimates to actual field tests, as described below. Because both the cost and the reliability of the estimates increases for more detailed methods, it is recommended that the basic estimation approaches be used first, and more detailed methods be used (if warranted) as project assessment progresses.

2.2.1 Methods for Estimating Gas Flow

Three gas flow estimation methods are presented below. The first two are relatively simple approaches that require limited site-specific information. Because landfill characteristics, and therefore gas generation rates, can vary substantially among landfills (even those with the same amount of waste in place), Methods A and B will provide only rough gas flow estimates. When using these methods, the landfill owner/operator should assume that actual gas flows may be 50 percent higher or lower. For example, lower gas flows may occur at landfills located in arid areas (i.e., receiving less than 25 inches of rainfall per year) or at landfills containing large amounts of construction/demolition debris. Method C, in contrast, relies on data from the landfill itself, and should provide more accurate estimates.

Method A: Simple Approximation

A *rough approximation* of landfill gas production can be estimated easily using the amount of waste in place as the only variable. The procedure described below for approximating gas production is derived from the ratio of waste quantity to gas flow observed in the many, often very different, projects in operation. It reflects the *average* landfill that has an energy recovery project, and may not accurately reflect the waste, climate, and other characteristics present at a specific landfill. Therefore, it should be used primarily as a screening tool to determine if a more detailed assessment is warranted (such as can be developed using Method C).

The simple approximation method only requires knowledge of how much waste is in place at the target landfill. Based on their extensive experience at many landfills, industry experts have developed a rule of thumb that landfill gas generation rates range from 0.05 to over 0.20 cubic feet (cf) of gas per pound (lb) of refuse per year, with the average landfill generating 0.10 Cf of landfill gas per lb per year [WMNA, 1992; Walsh, 1994].

Using this rule of thumb results in the following equation:

Annual Landfill Gas Generation (cf) = 0.10 cf/lb x 2000 lb/ton x Waste-In-Place (tons)

A sample calculation using this method is shown in Box 2.2. Because the amount of gas generated declines as waste ages in the landfill, the above gas generation estimate is only appropriate for the first year or two of project operation if no new waste is added. As a result, gas generation rates may be on the low end of the range for landfills that have been closed for several years. In addition, the landfill owner/operator should adjust downward his or her rough estimate of gas flows over the life of the project by 2 to 3 percent per year [Wolfe and Maxwell].

Box 2-2 Example Using Simple Approximation Method

For a landfill with one million tons of waste in place, this method yields a rough estimate of 200 million cubic feet of landfill gas per year, or about 550,000 cubic feet per day (cfd). The uncertainty associated with this estimate should be accounted for by adding and subtracting 50 percent, yielding a range for the landfill's gas flow of 275,000 to 825,000 cfd.

Method B: First Order Decay Model

The second approach — a "First Order Decay Model" — can be used to account for changing gas generation rates over the life of the landfill of a proposed project. Understanding the rate of gas flow over time is critical to evaluating project economics (see Chapter 5). The first order decay model is more complicated than the rough approximation described above, and requires that the landfill owner/operator know or estimate five variables:

- the average annual waste acceptance rate;
- the number of years the landfill has been open;
- the number of years the landfill has been closed, if applicable;
- the potential of the waste to generate methane; and
- the rate of methane generation from the waste.

The basic first order decay model is as follows:

$$LFG = 2\ L_0R\ (e^{-kc} - e^{-kf})$$

Where:

LFG	=	Total amount of landfill gas generated in current year (cf)
L_0	=	Total methane generation potential of the waste (cf/lb)
R	=	Average annual waste acceptance rate during active life (lb)
k	=	Rate of methane generation (1/year)
t	=	Time since landfill opened (years)
c	=	Time since landfill closure (years)

The methane generation potential, L_0, represents the total amount of methane that one pound of waste is expected to generate over its lifetime. Thus, it is much higher than the landfill gas generation constant used in Method A to represent landfill gas generation per year. The decay constant, k, represents the rate at which the methane will be released from each pound of waste. If these terms were known with certainty, the first order decay model would predict methane generation relatively accurately; however, the values for L_0 and k are thought to vary widely, and are difficult to estimate accurately for a particular landfill.

The values for L_0 and k are dependent in part on local climatic conditions and waste composition; therefore, a landfill owner/operator may want to consult others in the local area, with similar landfills who have installed gas collection systems to narrow the range of potential values. On March 12, 1996, EPA issued final regulations for the control of landfill gas at new and existing municipal solid waste landfills with design capacities of 2.5 million metric tons or more[1]. Affected landfills model their gas emissions using the first order decay model. The regulations include the following default values (as well as a non-methane organic compound default value of 4000 ppm, which a landfill can replace with site-specific data):

- L_0 = 2.72 cf/lb
- k = 0.05/year

Ranges for L_0 and k values developed by an industry expert are presented in Table 2-1. Note that for different climatic conditions, the L_0 (total amount of landfill gas generated) remains the same, but the k value (rate of landfill gas generation) changes, with dry climates generating gas more slowly.

Table 2-1 Suggested Values for First Order Decay Model Variables

Variable	Range	Suggested Values		
		Wet Climate	Medium Moisture Climate	Dry Climate
L_0 (cf/lb)	0-5	2.25-2.88	2.25-2.88	2.25-2.88
k (1/yr)	0.003-0.4	0.1-0.35	0.05-0.15	0.02-0.10

Source: Landfill Control Technologies, "Landfill Gas System Engineering Design Seminar," 1994.

Because of the uncertainty in estimating L_0 and k, gas flow estimates derived from the first order decay model should also be bracketed by a range of plus or minus 50 percent. Box 2.3 shows a sample calculation using the first order decay model.

Method C: Pump Test

The most accurate method for estimating gas quantity, short of installing a full collection system, is to conduct a pump test. A pump test involves sinking test wells and installing pressure monitoring probes, then measuring the gas collected from the wells under a variety of controlled extraction rates. When conducting a pump test, it is important that the

[1] 61 FR 9905, Tuesday March 12, 1996.

Box 2-3 Example Using First Order Decay Model

For a landfill with the following characteristics:

- open for 25 years;
- still accepting waste; and
- average annual waste acceptance rate of 40,000 tons

The first order decay model would yield a rough estimate of 310 million cubic feet of landfill gas per year, or about 850,000 cfd (using the NSPS k and L_0 values). The uncertainty associated with this estimate should be accounted for by adding and subtracting 50 percent, yielding a range for the landfill's gas flow of 425,000 to 1.3 million cfd.

Note that a landfill with the same amount of waste in place (i.e., one million tons) but a lower waste acceptance rate would have a lower gas flow rate, while a younger landfill that was taking in waste more quickly would have a higher gas flow rate. The choice of different values for k and L_0 in the first order decay model would also yield different gas flow estimates.

test wells are placed to be representative of the waste from which the gas will be eventually drawn, since gas generation rates may vary across the landfill.

A benefit of this method is that the collected gas can be tested for quality, as well as quantity. It should be analyzed for Btu content in addition to hydrocarbon, sulfur, particulate, and nitrogen content. Information obtained from a pump test is important since it is used in the design of the processing and energy recovery system, as well as in obtaining project financing.

The cost to drill test wells can range from $5,000 to $10,000 per well [Smithberger, 1994; Merry, 1994]. However, for budgetary purposes, the total cost of installing a well and extracting gas can be estimated to be approximately $60 per linear foot, with a typical test well being 100 feet deep [Bilgri, 1995]. This estimate includes costs for the well pipe, pipe casing, backfill, and labor. The total number of wells required to accurately predict landfill gas quantity will depend on factors such as landfill size and waste homogeneity.

Other Estimation Methods

Landfill gas energy recovery experts, if consulted by the landfill owner/operator, will almost certainly want to review and verify estimates developed using the above methods, particularly estimates developed with Methods A or B. Each energy recovery expert has his or her own preferred method for estimating landfill gas quantity, and will likely want to use this method to verify estimates prepared using any of the above methods.

2.2.2 Correcting for Collection Efficiency

Before gas generation estimates developed from Methods A or B are used to size a collection/energy recovery system, it is necessary to correct for landfill gas collection efficiency. There are several factors which affect the overall collection efficiency of a landfill gas extraction system, which can vary from about 50 to over 90 percent. The permeability of the landfill's cover layer will determine how much of the landfill gas generated will escape to the atmosphere; however, a portion of the landfill gas will escape through the cover of even the most tightly constructed and controlled collection system. Well spacing and depth, which are determined by economic and other site specific factors, also affect collection efficiency, as can bottom and side liners, leachate and water level, and meteorological conditions.

Collection systems operated for energy recovery may be more efficient than those where the collected gas is not put to productive use because each cubic foot of gas will have a monetary value to the owner/operator. In addition, newer systems may be more efficient than the average system in operation today. Nevertheless, there continues to be economic limits on the tightness of well spacing and other factors that are difficult or impossible to control. Therefore, a reasonable assumption for a newer collection system operated for energy recovery is 75 to 85 percent collection efficiency.

Multiplying the total landfill gas generation estimated by Methods A or B by 75 to 85 percent should yield a reasonable estimate of the landfill gas available for energy recovery. Even the results of Method C may have to be corrected for collection efficiency, since the results of the pump test may not provide an indication of gas flows across the landfill [Kraemer, 1995].

2.2.3 Comparing Your Gas Flow Rate to Existing Projects

For gas flow estimates to be meaningful, the landfill owner/operator must assess whether the available gas flow is sufficient to support an energy recovery project. The average energy recovery facility collects just over 2.5 million cubic feet per day (mmcfd) of landfill gas. However, the ability of a particular gas flow to support an energy recovery project is largely a function of the energy purchaser's or user's needs. Existing project sizes range from 20,000 cfd to over 30 mmcfd, and about one-third of the projects (existing and planned) use less than 1 mmcfd [Berenyi and Gould, 1994]. Two projects spanning much of this range are described in Box 2.4. Information on which project configurations are most cost-effective for a particular gas flow rate is provided in the next section and in Part II of this handbook.

Box 2-4 Energy Recovery at Two Very Different Landfills

Puente Hills Landfill

The Puente Hills Landfill in Whittier, CA, receives 12,500 tons of waste per day, and collects over 30 mmcfd from 400 vertical wells and 50 miles of horizontal collection piping. The Los Angeles County Sanitation Districts, which operates the landfills, uses the landfill gas in three ways:

- in a boiler/steam turbine configuration, located at the landfill, to generate almost 50 MW of power;
- as vehicle fuel, in the form of compressed natural gas;
- as fuel for a boiler at Rio Hondo college, located one mile away

Puente Hills is the largest landfill energy recovery power project in the United States. It has been operational since the early 1980s.

City of Keene. New Hampshire Landfill

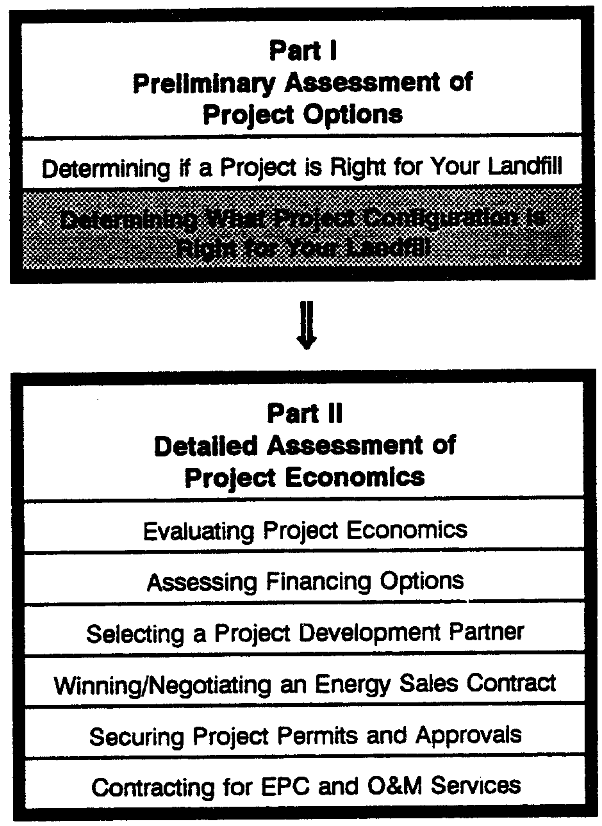
The City of Keene is using landfill gas from a 15 acre landfill to power its new recycling/transfer station. The station, located at the City landfill, requires three-phase electricity for its process machinery but the local electric utility's nearest three-phase power line stops several miles away from the site. By instead using gas from the landfill, the City will save more than $200,000 over the expected life of the landfill gas project.

A blower pulls the gas from 10 vertical wells, through simple particle and moisture filters to the (internal combustion) engine-generator set. The recycling/transfer station equipment runs 24 hours per day but is only heavily used during facility working hours. The landfill gas-to-energy system provides peak operating loads at about 180 kW, with the average over a full day at 50 kW. The project was built for a total of $280,000, including the gas collection system, and is expected to cost approximately $25,000 per year in operating costs. [Allan McLane, Vermont Energy Recovery]

3. DETERMINING WHAT PROJECT CONFIGURATION IS RIGHT FOR YOUR LANDFILL

After estimating the quantity of gas available for energy conversion, the landfill owner/operator must decide which conversion option or options make the most sense for the landfill (see Flowchart). Several options may be appropriate. The best choice will depend upon site-specific factors, including the characteristics of the landfill as well as local energy markets. Section 3.1 describes the basic energy conversion options and how a landfill owner/operator can assess which one(s) will be most cost-effective at his or her landfill. Section 3.2 compares the major energy recovery options on a cost basis for three landfill sizes.

The Project Development Process



An important consideration in the evaluation of energy conversion options is the availability of federal, state, or local incentives. For example, Section 29 of the Internal Revenue Service Code provides a tax credit for sale of landfill gas to an unrelated party, and the Department of Energy provides an incentive for publicly owned landfill gas facilities that generate electricity. Several states and some localities also provide incentives to landfill projects, such as low cost loan programs or other subsidies. Landfill owner/operators should determine if incentives are available and, if so, how a project must be structured to take advantage of them. (See Chapter 5 for more information on incentives).

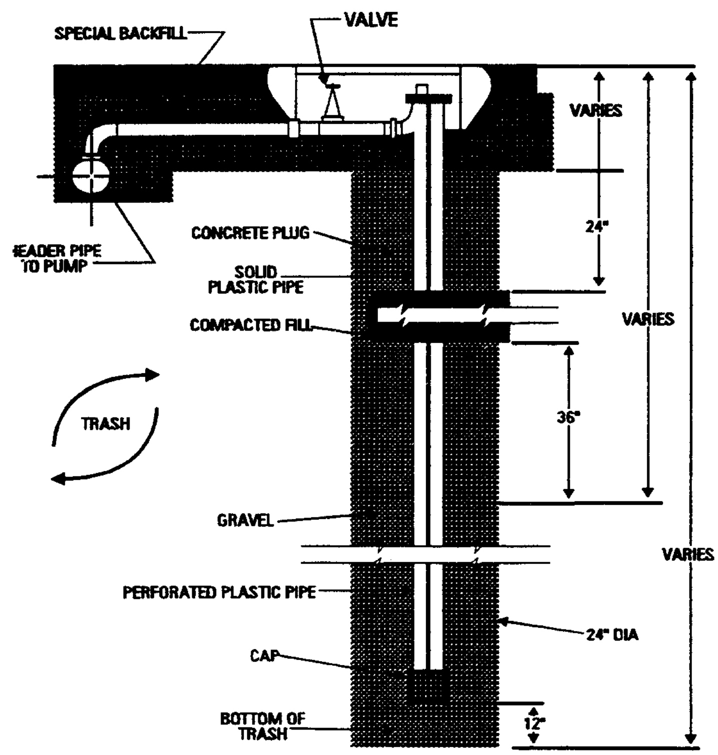
3.1 OPTIONS FOR USING LANDFILL GAS

Landfill gas can be converted into useable energy in a number of ways, including use as a fuel for internal combustion engines or turbines to produce electricity, direct use of the gas as a boiler fuel, and upgrade to pipeline quality gas, among others. Each of these options entails three basic components: (1) a gas collection system and backup flare; (2) a gas treatment system; and, (3) an energy recovery system. This section provides a brief overview of each component, and outlines the major characteristics of energy recovery systems that determine their applicability at a given site.

3.1.1 Collection System and Flare

Typical landfill gas collection systems have three central components: collection wells; a condensate collection and treatment system; and a compressor. In addition, most landfills with energy recovery systems will have a flare for the combustion of excess gas and for use during equipment down times. Each of these components is described below, followed by a brief discussion of collection system and flare costs. Figure 3.1 illustrates the design of a typical landfill gas extraction well, and Figure 3.2 shows a sample landfill gas extraction site plan.

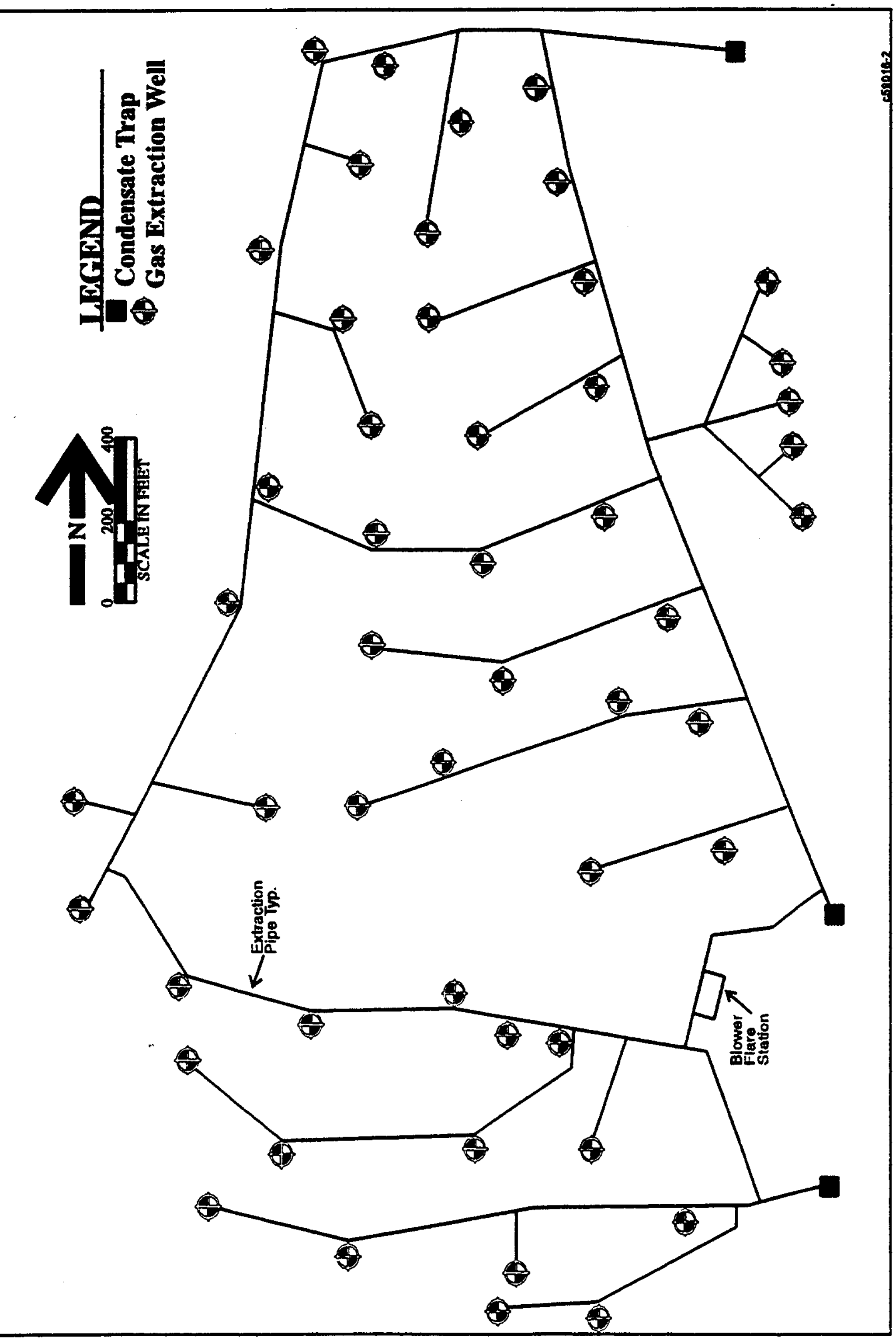
Figure 3-1 Typical Landfill Gas Extraction Well



Gas Collection Wells

Gas collection typically begins after a portion of a landfill (called a cell) is closed. There are two collection system configurations: vertical wells and horizontal trenches. Vertical wells are by far the most common type of well used for gas collection. Trenches may be appropriate for deeper landfills, and may be used in areas of active filling. Regardless of whether wells or trenches are used, each wellhead is connected to lateral piping, which transports the gas to a main collection header. Ideally, the collection system should be designed so that the operator can monitor and adjust the gas flow if necessary.

Figure 3-2 Sample Landfill Gas Extraction Site Plan



Condensate Collection and Treatment

An important part of any gas collection system is the condensate collection and treatment system. Condensate forms when warm gas from the landfill cools as it travels through the collection system. If condensate is not removed, it can block the collection system and disrupt the energy recovery process. Condensate control typically begins in the field collection system, where sloping pipes and headers are used to allow drainage into collecting ("knockout") tanks or traps. These systems are typically augmented by post-collection condensate removal as well. Some of the methods for disposal of condensate are discharge to the public sewer system, on-site treatment, and recirculation to the landfill. The best method for a particular landfill will depend upon the characteristics of the condensate (which may vary depending on site-specific waste constituents), regulatory considerations, and the cost of treatment and disposal.

Blower/Compressor

A blower is necessary to pull the gas from the collection wells into the collection header, and a compressor may be required to compress the gas before it can enter the energy recovery system. The size, type, and number of blowers and compressors needed depends on the gas flow rate and the desired level of compression, which is typically determined by the energy conversion equipment.

Flare

A flare is simply a device for igniting and burning the landfill gas. Flares are considered a component of each energy recovery option because they may be needed during energy recovery system startup and downtime. In addition, it may be most cost-effective to gradually increase the size of the energy recovery system and to flare excess gas between system upgrades (e.g., before addition of another engine). Flare designs include open (or candle) flares and enclosed flares. Enclosed flares are more expensive but may be preferable (or required) because they allow for stack testing and can achieve slightly higher combustion efficiencies. In addition, enclosed flares may reduce noise and light nuisances.

Collection System Costs

Total collection system costs will vary widely, based on a number of site specific factors, It the landfill is deep, collection costs will tend to be higher due to the fact that well depths will need to be increased. Collection costs also increase with the number of wells installed. Table 3-1 presents estimated capital and operating and maintenance costs for collection systems (including flares) at typical landfills with 1, 5, and 10 million metric tons of waste in place. For a landfill with 1 million metric tons of waste, collection system and flare capital costs will likely be approximately $628,000, increasing to about $2.1 million for a 5 million metric ton landfill and $3.6 million for a 10 million metric ton landfill. Annual operation and maintenance costs for the landfill gas collection system may range from $89,000 for the typical 1 million metric ton landfill, increasing to $152,000 for the 5 million metric ton landfill and $218,000 for the 10 million metric ton landfill. [All cost data are in 1994 dollars.]

Flaring costs have been incorporated into the estimated costs of landfill gas collection systems (which are presented in Table 3.1 and in more detail in Chapter 5), since excess gas may need to be flared at any time, even if an energy recovery system is installed. Flare systems typically account for 5 to 15 percent of the capital cost of the entire collection system (i.e., including flares). For a typical landfill with 1 million metric tons of waste in place, flare system capital costs will be approximately $88,000, increasing to about $146,000 for a 5 million metric ton landfill and $205,000 for a 10 million metric ton landfill.[1] Note, however, that flare costs will vary with local air pollution control monitoring requirements and the owner's own safety requirements. For example, if it is necessary to enclose the flare in a building for security or climatic reasons, the proceeding cost figures would increase by approximately $100,000 [Nardelli, 1993].

Annual operation and maintenance costs for flare systems are less than 10 percent of the total collection system costs, and thus range from approximately $8,000 for a 1 million metric ton landfill, increasing to $15,000 for a 5 million metric ton landfill and $21 ,000 for a 10 million metric ton landfill.

Table 3-1 Summary of Representative Collection System Costs* ($1994)

Landfill Size Waste in Place	Estimated Gas Flow (mcf/day)	Capital Costs ($000)	Annual O&M Costs ($000)
1 million metric tons	642	628	89
5 million metric tons	2,988	2,088	152
10 million metric tons	5,266	3,599	218

* Collection system costs include flaring costs.

3.1.2 Gas Treatment Systems

After the landfill gas has been collected, and before it can be used in a conversion process, it must be treated to remove any condensate that is not captured in the knockout tanks, as well as particulates and other impurities. Treatment requirements depend on the end use application. Minimal treatment is required for direct use of gas in boilers, while extensive treatment is necessary to remove CO_2 for injection into a natural gas pipeline. Power production applications typically include a series of filters to remove impurities that could damage engine components and reduce system efficiency.

The cost of gas treatment depends on the gas purity requirements of the end use application; the cost to filter the gas and remove condensate for power production is considerably less than the cost to remove carbon dioxide and other constituents for injection into a natural gas pipeline or for conversion to vehicle fuel. These costs are incorporated into the energy recovery system costs presented in Section 3.1.3 below.

[1] The costs quoted here refer only to the flare system which includes the flare and monitoring equipment. Other items such as the blower and condensate handling system have been reflected in collection system costs.

3.1.3 Energy Recovery System

The goal of a landfill gas-to-energy project is to convert landfill gas into a useful energy form such as electricity, steam, boiler fuel, vehicle fuel, or pipeline quality gas. There are several technologies that can be used to maximize the value of landfill gas when producing these energy forms, the most prevalent of which are:

(1) direct medium-Btu gas use
(2) power production/cogeneration
(3) sale of upgraded pipeline quality gas

The best configuration for a particular landfill will depend upon a number of factors including the existence of an available energy market, project costs, potential revenue sources, and many technical considerations. This section focuses on the technical issues that determine a project's feasibility, and, more specifically, on the technical issues related to direct use and power production, since these are the most common recovery options. Section 3.2 provides more information on choosing among the potential energy recovery technologies.

Option 1: Sale of Medium-Btu Gas

The simplest and often most cost-effective use of landfill gas is as a medium-Btu fuel for boiler or industrial process use (e.g., drying operations, kiln operations, and cement and asphalt production). In these projects, the gas is piped directly to a nearby customer where it is used in new or existing combustion equipment as a replacement or supplementary fuel. Only limited condensate removal and filtration treatment is required, but some modification of existing equipment may be necessary. There are currently about 30 direct use landfill gas projects in operation in the United States, and others are under development [Thorneloe, Pacey, 1994]. Box 3.1 provides specific examples of how landfill gas is being used as a medium-Btu fuel in some of these projects.

Before landfill gas can be used by a customer, a pipeline must first be constructed to access the supply. Pipeline construction costs can range from $250,000 to $500,000 per mile;[2] therefore, proximity to the gas customer is critical for this option. Often, a third party developer is involved in the project who will assume the cost of installing the pipeline.

The customer's gas requirements are also an important consideration when evaluating a sale of medium-Btu gas. Because there is no economical way to store landfill gas, all gas that is recovered must be used as available, or it is essentially lost, along with associated revenue opportunities. Therefore, the ideal gas customer will have a steady, annual gas demand compatible with the landfill's gas flow. In situations where a landfill's gas flow is not enough to support the entire needs of a facility, it may still be used to supply a portion of needs. For example, some facilities have only one piece of equipment (e.g., a main boiler) or set of burners dedicated to burn landfill gas. They also may have equipment that can use landfill gas along with other fuels.

Table 3-2 gives the expected annual gas flows on a MMBtu basis from different sized landfills. While actual gas flows will vary, these numbers may be used as a first step toward determining the compatibility of customer gas requirements and landfill gas output. A general

[2] Pipeline construction costs vary due to terrain differences, right-of-way costs, and other site-specific factors.

Box 3.1 Examples of Direct Use Applications

- The City of Industry, CA has found several uses for landfill gas at its Recreation/Convention Center. Landfill gas is used in boilers to provide hot water for laundry and space heating for the Convention Center. The medium-Btu fuel is also used to heat the Center's swimming pool.
- The Kentucky-Tennessee Clay Company, located in Aiken County, SC, burns landfill gas in its rotary dryer to dry kaolin clay before shipment.
- Ogden Martin Systems, Inc. operates a waste-to-energy plant in Huntsville, AL to supply the steam needs of the U.S. Army's Redstone Arsenal. Landfill gas is used in a supplementary boiler at the waste-to-energy plant to meet the Arsenal's additional steam needs during peak demand periods [Mahin, 1991].
- In Langely, British Columbia, landfill gas is used in a greenhouse to provide heating and CO_2 for growth enhancement (Thorneloe, Pacey, 1994].
- Methane collected from the Acme Landfill in Martinez, CA is used at the Contra Costa Wastewater Treatment Facility.

rule of thumb to use when comparing boiler fuel requirements to landfill gas output is that approximately 8,000 to 10,000 pounds per hour of steam can be generated for every 1 million metric tons of waste in place at a landfill.[3] Using this rule of thumb, it can be estimated that a 5 million metric ton landfill would support the needs of a large facility requiring about 50,000 pounds per hour of steam for process use.

Table 3-2 Landfill Gas Flows Based on Landfill Size

Landfill Size	1 MM Mg	5 MM Mg	10 MM Mg
LFG Output (MMBtu/year)[1]	100,000	490,000	850,000
Steam Flow Potential (lbs/hr)	10,000	45,000	85,000

[1] Assumes a 90% capacity (i.e., availability) factor
Output figures reflect rounding

If an ideal customer is not accessible, then it may be possible to create a steady gas demand by serving multiple customers whose gas requirements are complementary. For example, an asphalt producer's summer gas load could be combined with a municipal building's winter heating load to create a year-round demand for landfill gas.

[3] This rule of thumb is based on steam delivery at 50 psig, saturated.

Equipment modifications or adjustments may be necessary to accommodate the lower Btu value of landfill gas, and the costs of modifications will vary. Costs will be minimal if only boiler burner retuning is required. However, boiler burner retrofits are typically customized, and total installation costs can range from $120,000 for a 10,000 lb/hr boiler to $300,000 for an 80,000 lb/hr boiler (Brown, 1995]. As with pipeline construction costs, a third party project developer may assume the costs of equipment modifications or additions. This was the case when Natural Power, Inc. paid $600,000 to install a new 26,000 lb/hr Cleaver-Brooks boiler to burn landfill gas to serve the steam needs of Ajinomoto USA, Inc., a pharmaceutical plant [Augenstein, Pacey, 1992].

Operation and maintenance (O&M) costs associated with using landfill gas in boilers, kilns, dryers, or other industrial equipment are typically equivalent to 0&M costs when using conventional fuels. In general, 0&M costs will depend on how well the equipment is maintained and how well the gas collection system is controlled. Some 0&M considerations when using landfill gas as a medium-Btu fuel are listed in Box 3.2.

Box 3.2 Considerations When Using Landfill Gas as a Medium-Btu Fuel

It is important to consider the unique aspects of collecting and using landfill gas in equipment such as boilers, kilns, or dryers. Examples of considerations that can help to ensure optimal equipment performance include:

- Moisture content — Landfill gas generally has three to seven percent moisture when it is collected. Sloped piping and condensate traps must be used to avoid water blockage in landfill gas piping or blowers which can be a cause of system interruptions (e.g., water can trip a gas blower or cause a loss of flame in a boiler).

- Lower flame temperature — Landfill gas has a lower flame temperature than natural gas, and thus may result in lower superheater temperatures in boilers. Boilers may therefore require larger superheaters to accommodate the use of landfill gas.

- Lower Btu value — The heating value of landfill gas can be reduced if collection wells draw in large amounts of air or if breaks in the collection piping occur. Good design and operating practices can prevent such problems [Eppich and Cosulich, 1993].

Option 2: Power Generation

The most prevalent use for landfill gas is as a fuel for power generation, with the electricity sold to a utility and/or a nearby power customer. Power generation is advantageous because it produces a valuable end product — electricity — from waste gas. Facilities that use landfill gas to generate electricity can qualify as a "small power producer" under the Public Utilities Regulatory Policy Act (PURPA), which requires electric utilities to purchase the output from such facilities at the utility's avoided cost. The electricity can in some cases be used on-site to displace purchased electricity or be sold to a nearby electricity user (e.g., municipality, industrial).

Cogeneration is an alternative to producing electricity only. Cogeneration systems produce electricity and thermal energy (i.e., steam, hot water) from one fuel source. Whereas the thermal efficiencies of electricity-only generation range from 20% to 50%, cogeneration systems can achieve substantially higher efficiencies by puffing to use the "waste" heat that is a by-product of most power generation cycles. Thermal energy cogenerated by landfill gas projects can be used on-site for heating, cooling, and/or process needs, or piped to a nearby industrial or commercial user to provide a second revenue stream to the project.

Several good conversion technologies exist for generating power — internal combustion engines, combustion turbines, and boiler/steam turbines — each of which is described below. Box 3.3 highlights important aspects of each option. In the future, other technologies, such as fuel cells, may also become commercially available. Box 3.4 provides some discussion on the design considerations when sizing a landfill gas power project.

Internal Combustion Engine

The reciprocating internal combustion (IC) engine is the most commonly used conversion technology in landfill gas applications; almost 80 percent of all existing landfill gas projects use them [Thorneloe, 1992]. The reason for such widespread use is their relatively low cost, high efficiency, and good size match with the gas output of many landfills. In the past, the general rule of thumb has been that IC engines have generally been used at sites where gas quantity is capable of producing 1 to 3 MW [Thorneloe, 1992], or where landfill gas flows are approximately 625,000 to 2 million cubic feet per day at 450 Btu per cubic foot [Jansen, 1992].

IC engines are relatively efficient at converting landfill gas into electricity. IC engines running on landfill gas are capable of achieving efficiencies in the range of 25 to 35 percent. Historically, these engines have been about 5 to 15 percent less efficient when using landfill gas compared with natural gas operation, although the newest engine designs now sacrifice less than 5 percent efficiency when landfill gas is used [Augenstein, 1995]. Efficiencies increase further in cogeneration applications where waste heat is recovered from the engine cooling system to make hot water, or from the engine exhaust to make low pressure steam. IC engines adapted for landfill gas applications are available in a range of sizes, and can be added incrementally as landfill gas generation increases in a landfill.[4]

Environmental permitting may be an issue for some IC engine projects. IC engines typically have higher rates of nitrogen oxide (NO_x) emissions than other conversion technologies, so in some areas it may be difficult to obtain permits for a project using several IC engines. To address this problem, engine manufacturers are developing engines that produce less NO_x using improved combustion and other air emission control features. These advances should give plant designers more flexibility to use IC engines on large projects.

The installed capital costs for landfill gas energy recovery projects using IC engines are estimated to range from about $1,100 per net kW output to $1,300 per net kW output (1996 on-line date). These costs are indicative of power projects at landfills ranging in size from 1

[4] The most commonly used IC engines for landfill gas applications are rated at about 800 and 3,000 kW.

Box 3.3 Comparison of Electricity Generation Technologies

	IC Engines	Combustion Turbines	Steam Turbine/Boiler
Typical Project Size (MW)	≥ 1	> 3	> 8
Landfill Gas Requirements (mcf/day)	≥ 625	> 2,000	> 5,000
Typical Capital Costs ($/kW)	1,100 - 1,300	1,200 - 1,700	2,000 - 2,500
Typical O&M Costs (¢/kWh)	1.8	1.3 - 1.6	1.0 - 2.0
Electric Efficiency (%)	25 - 35	20 - 28 (CT) 26 - 40 (CCCT)	20 - 31
Cogeneration Potential	Low	Medium	High
Compression Requirements (Input Gas Pressure (psig))	Low (2 - 35)	High (165+)	Low (2 - 5)
Advantages	• Low cost • High efficiency • Most common technology	• Corrosion resistant • Low O&M costs • Small physical size • Low NO_x emissions	• Corrosion resistant • Can handle gas composition and flow variations
Disadvantages	• Problems due to particulate matter buildup • Corrosion of engine parts and catalysts • High NO_x emissions	• Inefficient at part load • High parasitic loads, due to high gas compression requirements	• Inefficient at smaller sizes • Requires large amounts of clean water • High capital costs

* All costs reflect a 1996 on-line date.

Box 3.4 Design Considerations When Sizing Power Projects

Determining the optimum size for a landfill gas power project requires a careful balance between maximizing electricity production and landfill gas use, and minimizing the risk of insufficient gas supplies in later years. The challenge arises because landfill gas production rates change over time. Gas generation may be increasing at an open landfill or decreasing at a closed landfill. System designers must also consider factors such as current and future electricity payments, equipment costs, and any penalties for shortfalls in electricity output.

The optimum design and operating scenario for a particular landfill gas project is likely to fall somewhere between two general scenarios: (1) minimum gas flow design; and (2) maximum gas flow design. However, a third design scenario — a modular approach — may be used at landfills where gas flow rates are expected to change substantially over time.

(1) Minimum Gas Flow Design. In this scenario, the electric generation equipment is sized based on the minimum expected gas flows over the life of the project. This ensures that the fuel supply (i.e., landfill gas) is seldom or never limited, and the electric generation system always runs at or near its maximum availability. This is a more conservative design, which puts a premium on constant and reliable electrical output over the project life. The disadvantage of this design is that some landfill gas will go unused in years when gas is plentiful; a lost opportunity to generate electricity and earn revenues. This may be a good design choice when project economics are robust and substantial contract penalties exist for shortfalls in electrical deliveries from the project. Capacity factors for this type of project are determined mainly by the generating equipment outage rates, which are approximately 6% to 10% for IC engine systems and 4% to 6% for combustion turbine-based systems.

(2) Maximum Gas Flow Design. In this scenario, the electric generating equipment is sized based on maximum gas flows over the life of the project. Landfill gas usage and electrical output are generally maximized, but there may be occasions when there is insufficient landfill gas supply to run the generating equipment at its rated capacity. This is a more aggressive design which puts a premium on full utilization of the landfill gas, and it has the advantage of higher electrical generating capacity, revenues, and landfill gas utilization than the first scenario. However, the disadvantages are that the project may suffer from periods when electrical output is below the rated capacity because of intermittent gas supply shortages or declining landfill production. This is an acceptable design if maximizing early-year revenues is critical, the power purchase contract is short-term, shortfall penalties are nonexistent, and/or alternate or augmented fuel supplies exist. Capacity factors for this type of project are determined by generating equipment outage rates and expected periods when fuel supply is limited. Part-load generating efficiency is a consideration in this type of project; IC engines and fuel cells generally exhibit better part-load performance (e.g., efficiency, wear) than CT-based systems.

(3) Changing Gas Flow Design. In this scenario, a series of smaller electric generating units is installed (or removed) over time as gas flow rate increases (or decreases). This modular approach helps ensure that landfill gas output is properly matched to equipment size, even when gas flow rates change. This approach has the dual benefit of maximizing gas use and electric output over time. However, a modular approach may also produce higher installation costs and lower efficiencies than other approaches. If gas flow is decreasing over time, designers must consider what to do with units that are no longer useful.

million metric tons to 10 million metric tons of waste in place, and the costs include the engine, auxiliary equipment, interconnections, gas compressor, construction, engineering, and soft costs. (Chapter 5 provides more detail on technology costs.) The costs associated with the landfill gas collection system are not included in these cost estimates.